Digital data storage in a phase-encoded holographic memory system: data quality and security

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ABSTRACT

We review the crucial properties of a phase-encoded volume holographic storage system in terms of data quality and security, which are the key issues of any bulk memory system. Two major problems which need to be tackled in holographic storage systems in terms of data quality are the hologram erasure during readout and the data encoding schemes for error-free reconstruction. We present a novel storage material (bismuth tellurite crystals - Bi_2TeO_5) which has the potential to overcome the volatility problem and avoiding the need of any further fixing. Regarding data encoding schemes, we present a general approach of gray-scale modulation coding in order to improve the data capacity in comparison to normal modulation coding, while the bit error rate maintains low. Data security in a phase-encoded system can be realized by exploiting its special multiplexing characteristics. We present different encryption techniques and investigate their decryption probability.

Keywords: Volume holography, phase-code multiplexing, non-volatile holographic storage, modulation coding, data encryption, random phase encoding

1. INTRODUCTION

During the last years volume holographic storage systems have impressively demonstrated their capabilities in terms of storage capacities which reach 1 TByte/cm^3, fast data transfer rates which can exceed 10 GBit/s and short random access times of less than 100 μs.[1,2] These features are achieved by the page-oriented storage principle and the use of multiplexing techniques like angular, wavelength and spatial multiplexing or any variants and combinations of them (e.g.[3–7]). Among the different multiplexing techniques orthogonal phase-code multiplexing offers several advantages. Most attractive is perhaps its feature of operating with a fixed wavelength and at the same time avoiding mechanically moving components. Moreover, the signal-to-noise ratio is in the range of two orders of magnitude higher than for the widely spread angular multiplexing.[8,9] Additionally, the special characteristics of orthogonal phase-code multiplexing allow to perform optical arithmetic operations as addition, subtraction or inversion directly during readout and enable very potential data encryption techniques.[10,11]
Nevertheless volume holographic storage systems still suffer from the lack of a memory material which has to fulfil a series of properties, e. g. it should possess a high sensitivity, a great optical quality and a large dynamic range while it is cheap, robust and prevents from data loss due to hologram volatility. In this paper we present a new storage material which combines the advantages of the anorganic lithium niobate crystals, but overcomes the vulnerability of the holograms. Another subject of permanent investigations in terms of data quality in page-oriented optical systems are the data encoding schemes, which should enhance the bit error rate (BER) at minimal capacity losses.[12] In this context we discuss a general approach on the implementation of gray values in the powerful modulation coding technique.
In section 5 we concentrate on the high potential for securing data in phase-encoded storage systems, which was revealed in several works.[13–17] It became apparent that our recent success in implementing associative recall also in a phase-encoded system,[18] in which we managed to overcome the necessity of phase measurements, has far-reaching consequences for the address based encryption techniques. Therefore, we briefly review the principles of the most effective encryption techniques which exploits the special characteristics of phase-encoding and discuss their amount of security in view of these recent investigations.

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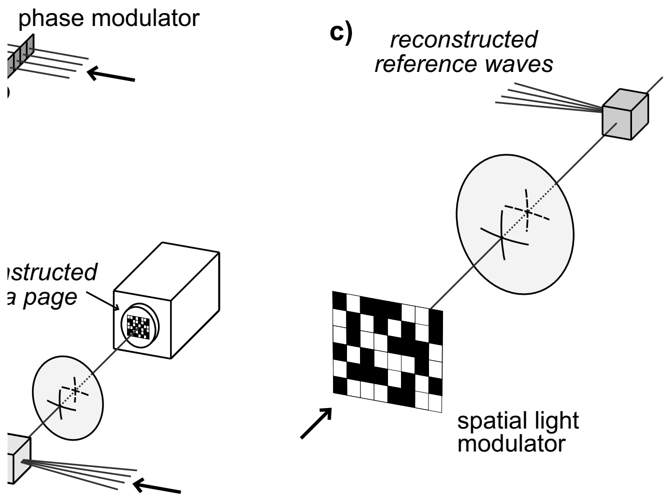

Figure 1. Principle of a phase-encoded storage system: a) storage process, b) address based recall, i. e. data page reconstruction, c) content-addressed recall.

2. BASICS OF PHASE-CODE MULTIPLEXING

The storage process in a phase-encoded system is in principle sketched in fig. 1a. In the signal arm the data to be stored are impressed onto the signal wave by a spatial light modulator (e. g. a LCD). Then the wave is focused into the storage material where it interferes with a discrete set of N angularly separated reference beams. As in angular multiplexing each of these reference beams obey the Bragg condition. The difference of phase-code multiplexing is that all these reference beams interfere simultaneously with the signal wave. In order to store further data pages in the same location all these reference beams are used again, but for each page their phases are individually readjusted by a phase modulator (typically a ferro-electric or nematic LCD). The single phase shifts are either 0 or π and the whole set of shifts corresponding to a certain data page is called its phase code or its address in the storage medium. For recalling one of the stored pages the appropriate phase-code has to be readjusted and the storage medium is again illuminated with all reference beams. In this step actually all written holograms are reconstructed, but due to the use of orthogonal phase-codes not-addressed data pages will interfere destructively and the addressed page can be detected without any cross talk as sketched in fig. 1b. This principle of destructive interference gives rise to the significantly higher signal-to-noise ratio of this method compared to other multiplexing techniques.[8] In order to achieve this feature the accuracy of the adjusted phase shifts must be close to the theoretical values within about 1%.[13]

In order to perform an associative recall, as sketched in fig. 1c, the storage medium is addressed with any data page. This results in the reconstruction of the appropriate reference beams, being phase-modulated with the same pattern which was used for storing that page. If the information used for addressing is contained on several stored data pages each reconstructed reference beam is actually a mixture of several reconstructed beams which interfered constructively and destructively. Intentionally content-addressing was motivated by the aim to enable simultaneous searches in entire databases by performing the correlation of the stored data pages with a page used for addressing (e. g. [19]). This feature of volume holographic memories was first demonstrated in systems based on angular multiplexing.[20–22] In phase-encoded systems the characteristic phase pattern of the reference beams which gives information about the address of a certain data page is not directly visible. This problem was recently solved by specific symmetry breaking of the destructive and constructive interference of the orthogonal phase codes which yield to characteristic intensity distributions of the reconstructed reference beams.[18] In section 5.2 it is described how content-addressing can be exploited in order to increase the probability of cracking random phase encryption. For this purpose one is especially interested in the phases of the reference beams rather than the produced intensity distributions, since in this case their composition is not comprehensible.

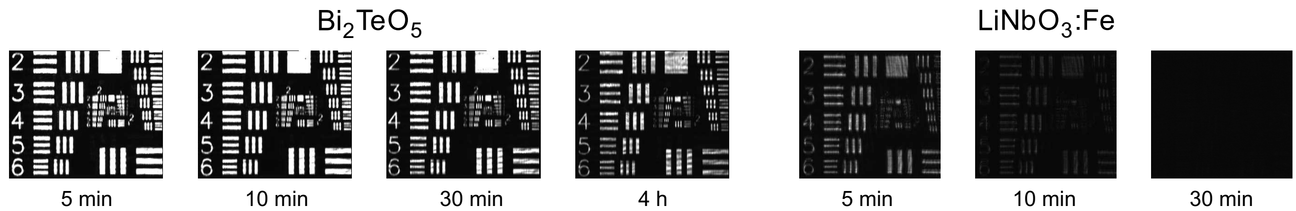

Figure 2. Permanent reading in Bi_2TeO_5 and $LiNbO_3$:Fe.

3. DURABLE HOLOGRAMS IN BISMUTH TELLURITE

One of the major limitations for a breakthrough of volume holographic data storage systems is the lack of proper memory materials. Various types of materials like anorganic crystals, polymers and glasses have been proposed. Among these materials iron doped $LiNbO_3$ is still the best in terms of the optical quality. However, these kinds of anorganic photorefractive crystals typically suffer an inconvenient volatility of the written holograms.

Optically nonlinear bismuth tellurite crystals, Bi_2TeO_5, have the potential to overcome this volatility problem. Early studies of Bi_2TeO_5 revealed that a photorefractive signal component which developed in a two wave mixing process lasted for several years without any specific fixing.[23–25] The crystals investigated in our experiments were grown by the diameter controlled Czochralski technique. The technical details of the raw material preparation and crystal growth are described in [[26]]. As a reference material iron doped, single domain lithium niobate was used. The congruent $LiNbO_3$ crystals were grown by the Czochralski technique in air ambient. The Fe-concentration was adjusted to be 10^{-3} mole/mole.

The signal decay of holograms in Bi_2TeO_5 undergoes three different phases. In the first phase which lasts about 10 s a strong signal decay is discernible. Then for several minutes a much slower signal decay takes place. In the third phase the signal maintains mainly unchanged and the hologram can be permanently read out without any further losses. The diffraction efficiency of the long lifetime component is approximately 10% of the initial diffraction efficiency. Fig. 2 depicts qualitatively the erasure process under permanent reading in Bi_2TeO_5 and $LiNbO_3$, in which the modulation depth of the holograms after the writing, the initial diffraction efficiency and the reading intensity were adjusted to be equal in both cases.

The origin of the long term stability of the holograms written in Bi_2TeO_5 has not been identified unambiguously. Two explanations are currently under discussion. One approach presumes that the effect is related to deep trap levels. But due to the position of the 3.1 eV absorption edge their presence is not very likely. The second explanation suggests that the effect is related to the large structural oxygen deficiency (17%) of the Bi_2TeO_5 crystals. Oxygen ion transfer driven by the photorefractive space charge field might lead to "self-fixing" of the signal. Thereby the electro-optically induced refractive index change is converted into an electrically neutral modulation of the spatial oxygen distribution.[24] The experimentally observable slight enhancement of the hologram contrast during the dark decay supports this model.

4. GRAY-SCALE MODULATION CODING

This section is devoted to modulation coding and the potential of gray value implementation. Various types of modulation coding have been discussed in several publications and also the combination with gray-scaling was investigated.[12, 27–29] Here we present a general approach to gray-scale modulation coding in which we emphasize the constant brightness feature of the encoded data pages. This feature ensures constant diffraction efficiencies of each written hologram, which is of major interest since it is the precondition for low cross-talk and high signal-to-noise ratios. Finally we present a general construction rule for these codes.

4.1. Basics of constant-weight modulation coding

The simplest bit detection scheme is global threshold detection, but mainly due to spatial intensity variations this technique yields typically low bit error rates. Several more sophisticated bit detection schemes have been proposed. In parallel optical systems especially modulation coding and inverse filtering are powerful tools for

user word		(1,2,1)-code
0	$\leftrightarrow$	01
1	$\leftrightarrow$	10

user word		(2,4,1)-code	(2,4,3)-code
00	$\leftrightarrow$	0001	1110
01	$\leftrightarrow$	0010	1101
10	$\leftrightarrow$	0100	1101
11	$\leftrightarrow$	1000	0111

Table 1. Possible assignments of the (1,2,1), the (2,4,1) and the (2,4,3) modulation code

user word		$\left(2,3,\frac{3}{2}\right)$		
00	$\leftrightarrow$	0	0.5	1
01	$\leftrightarrow$	0	1	0.5
10	$\leftrightarrow$	1	0	0.5
11	$\leftrightarrow$	1	0.5	0

Table 2. Possible assignment of the (2,3,1.5) modulation code which utilizes 3 gray values

reducing the bit error rate (BER), since they take the parallelism of the storage process into account. These techniques can of course be combined with common error correction coding (e. g. Reed-Solomon codes). An important measure for any error reduction technique is its code-rate, which is given as the ratio of the user bits to the total bits of a data stream, i. e. it is the fraction of the theoretical storage capacity which is actually used for encoding user data. Inverse filtering equalizes the expected diffraction efficiencies of each ON bit of the data page by adapting the exposure times of the bits.[29] Therefore this technique does not reduce the storage capacity and hence its code-rate is equal to 1.

Modulation coding separates the data page in equally sized blocks of constant bit numbers b. Each of these blocks consists of equal numbers of 1s (ON bits) and 0s (OFF bits) and is capable of encoding d user bits. Due to the constant number w of 1s such codes are also referred to as constant-weight codes.[27] The user data is detected by searching for the brightest bits of a block and identifying them as 1s. Hence, a certain modulation code can be characterized by the triplet (d, b, w). Table 1 shows the simplest modulation code (1,2,1) which is often called differential code and the (2,4,1) code and its inverse code.

The general construction rule for that kind of modulation codes can be written as

$$2^d \leq \binom{b}{w}. \tag{1}$$

For instance, in order to encode any user word of size $d = 4$ the modulation code must be capable to distinguish between at least $2^4 = 16$ different words. In the case $d = 4$ this requirement is fulfilled by a code of block size $b = 6$ and weight $w = 3$, since $(6 \textit{ choose } 3) = 20 > 16$.

Therefore, this technique realizes local threshold detection and hence reduces bit errors due to spatial intensity variations. Moreover this technique guarantees constant brightness w/b of all data pages. In terms of volume holographic data storage this is very desirable in order to control the exposure time during recording in such a way that at any time the diffraction efficiency of each hologram is the same. The code-rate of a modulation code is given by d/b. Consequently higher code-rates can be achieved by bigger block sizes at the expense of higher BERs.[27]

4.2. Implementation of gray values

The basic idea of gray-scale modulation coding is to increase the code-rate while the BER remains low by allowing more than the two (1s and 0s) discrete gray values in a data page. Each block bit is able to display any of n different gray values of weight $w_{1,\ldots,n}$, where $w_i \epsilon [0, 1]$ is the relative brightness of the i-th gray value. Additionally the absolute frequencies of the different gray values per block are supposed to be constant in order to guarantee equal brightness of each data page. The simplest code utilizing 3 gray values (e. g. $w_1 = 1, w_2 = 0.5$ und $w_3 = 0$) is the (2,3,1.5)-code in which 2 user bits are represented by 3 block bits. A possible assignment is depicted in table 2. The code-rate of this code is 0.67 and the brightness is 0.50. When using two gray values (just 1s and 0s) at least block sizes of 6 bits are required to achieve the same code rate. If 4 gray values are

utilized the (4,4,2)-code is the simplest code. Its code-rate is 1.00 and its brightness 0.50.
The general construction rule for any constant-weight code utilizing i gray values can be written as

$$2^d \leq \binom{b}{m_1} \cdot \binom{b-m_1}{m_2} \cdot \binom{b-m_1-m_2}{m_3} \cdots \binom{b-\sum_i^{n-1} m_i}{m_n} = \frac{b!}{\prod_i m_i!}\,, \tag{2}$$

where b is the number of bits per block and m_i is the absolute frequency of the i-th gray value. For instance, a user word which consists of 6 bits could be any one from a set of $2^6 = 64$ words. Therefore, when utilizing 3 gray values each block has to consist of at least $b = 6$ bits. In this case the maximal number of representable code words is 120. Such a profusion is a typical feature of these modulation codes and it suggests the implementation of soft error correction coding or the increase of the Hamming distance. In general it is obvious from the condition given in 2 that any code yields the most code words if the absolute frequencies of the different gray values per block are as much as possible equalized. Some example codes are given in table 3.
It is obvious that small block sizes which emphasizes best BERs lead to low code-rates. Therefore it is desirable to implement modulation codes of bigger sizes. In order to minimize the increasing errors due to intensity variations a modified inverse filtering is currently investigated in our experiment. This inverse filtering does not affect the constant overall brightness feature of the gray-scaled data pages.

user bits	block size	weight	abs. frequencies	code-rate	brightness
d	b	$w = \sum_i m_i \cdot w_i$	m_i	$r = \frac{d}{b}$	$h = \frac{g}{b}$
N=2 (w_1=1, w_2=0)					
1	2	1	1,1	0.5	0.5
2	4	1	1,3	0.5	0.25
6	8	4	4,4	0.5	0.25
8	12	4	4,8	0.67	0.33
12	15	6	6,9	0.80	0.40
N=3 (w_1=1, w_2=0.50, w_3=0)					
3	4	1.5	1,1,2	0.75	0.38
4	5	2	1,2,2	0.80	0.40
6	6	3	2,2,2	1.00	0.50
15	12	6	4,4,4	1.25	0.50
N=4 (w_1=1, w_2=0.67, w_3=0.33, w_4=0)					
4	4	2	1,1,1,1	1.00	0.50
7	6	2.33	1,1,2,2	1.17	0.39
14	10	4.33	2,2,3,3	1.40	0.43
18	12	6	3,3,3,3	1.50	0.50

Table 3. Exemplary modulation codes utilizing 2, 3 and 4 gray values

5. DATA ENCRYPTION IN PHASE ENCODED SYSTEMS

It is a primary objective of a bulk memory system to provide a high amount of data security. The straightforward encryption technique in a volume holographic storage system is to superimpose the data to be stored by random phase patterns, e. g. a random phase plate. During readout the data page is decrypted by passing again through that phase plate. Such a technique corresponds to common data encryption methods which are based on digital XOR-operations. Like in classical Vernam ciphering the original information is encrypted by applying a random data stream and decrypted by applying it a second time.
However, a phase encoded holographic system enables much more efficient data encryption schemes by exploiting

its specific multiplexing characteristics. One method is to distribute the information over several data pages by using optical arithmetic image operations. A second method is based on the combination of random and orthogonal phase code multiplexing. These two methods differ from other encryption techniques since they do not encrypt the information itself but its address in the storage medium.[17] In the following sections the principles of these methods are presented and the achievable level of security is investigated.

5.1. Principles of address-based data encryption

5.1.1. Encryption by arithmetic image operations

The basic idea of this encryption method has its seeds in the opportunity of phase encoded storage systems to enable optical arithmetic operations. By reducing the selectivity of the phase codes of the reference waves during readout it is possible to perform optical addition, subtraction or inversion of any data page and any number of data pages stored in one location. That is, OR, XOR and NOT operations can be performed when using digital data pages.

This special feature can be exploited in terms of data encryption by distributing the original information over several data pages before storing. These pages are then stored by the use of the deterministic orthogonal phase codes. In order to reconstruct actual information the proper combination of data pages have to be addressed. Addressing with a simple orthogonal phase code reconstructs just a meaningless mixture of information. The effectiveness of this method depends on the number of data pages which can independently be stored in one storage location, i. e. it depends on the number of independent linear combinations of the used phase codes. Therefore the decryption possibility is given by

$$P_a(N) = \left[\sum_{i=0}^{n-1} 2^i \cdot \binom{N}{2^i} \right]^{-1} , \tag{3}$$

where $N = 2^n$ is the number of data pages. The following table shows some values of $P_a(N)$

N	64	256	512
$P_a(N)$	$1.7 \cdot 10^{-20}$	$1.4 \cdot 10^{-78}$	$8.3 \cdot 10^{-156}$

.

5.1.2. Encryption by combining random and orthogonal phase-code multiplexing

This method exploits the matter of fact that only relative phase shifts in the reference arm are of significance for the storage process. That is, a distortion of the orthogonal phase codes by an additional random phase pattern has no influence on the selectivity of the codes if that distortion remains constant during recording and reconstruction. The phase pattern can be introduced by a random phase plate in the reference arm or directly by the phase modulator itself. Reading out with simple orthogonal phase codes results in meaningless mixtures of many actual data pages. The straightforward method to crack such a random phase key is to add additional random phase shifts by the phase modulator to each single reference beam during readout. The decryption probability for this cracking method is given by

$$P_r(N) = k \cdot \frac{(N/k)!^k}{N!} , \tag{4}$$

where N is the number of stored data pages and k is a measure of the required exactness of the guessed random shifts. For example, if $k = 5$ it is assumed that guessing a phase in the interval $\pm(\pi/5)/2$ around the correct value is sufficient enough for proper reconstruction. The following table gives some values of $P_r(N)$ where k is supposed to be 5

N	64	256	512
$P_r(N)$	$2.8 \cdot 10^{-41}$	$2.7 \cdot 10^{-174}$	$1.2 \cdot 10^{-352}$

.

5.2. Data security

The low decryption probabilities of these address based encryption technologies demonstrate their high data securing potential. However, angular and phase-code multiplexed systems also allow content-addressed recall which yields the storage address of a data page as sketched in figure 1c. This special feature can be exploited to drastically increase the decryption probability of the combined random and orthogonal phase-code method described in section 5.1.2. The idea is to address the storage medium by data pages containing just one or a few ON bits. Then, in an elaborate setup the phases of the reconstructed reference beams can be measured. Each of these phases emerge from constructive and destructive interference of 0 and π phase shifts of any orthogonal phase codes and the additional random phase shift. This means a proper set of phases for reconstructing an actual data page can be constructed by the measured phases and the measured phases plus a π phase shift. In consequence the probability of guessing any proper phase set is given by

$$P_{r,m}(N) = \frac{N}{2^{N-2}}\,, \tag{5}$$

where N is the number of reference beams which is equivalent to the number of stored data pages. The following table shows some values of the modified probability function

N	64	256	512
$P_{r,m}(N)$	$1.4 \cdot 10^{-17}$	$8.8 \cdot 10^{-75}$	$1.5 \cdot 10^{-151}$

In comparison to the decryption probability $P_a(N)$ given in section 5.1.1 these values reveal that the encryption method by arithmetic operations is more efficient. But in order to increase the decryption probability of the random phase encryption in that way a very sophisticated setup is required. It need to be capable of exact phase measurements of the reconstructed reference beams during a content addressed recall.

6. CONCLUSIONS

In this paper we discussed several aspects of volume holographic storage systems in terms of data quality. We first presented bismuth tellurite as an alternative storage material. In comparison to the widely spread lithium niobate it has the great advantage to overcome the hologram volatility due to a self-fixing effect, although further improvements in terms of the optical quality and the material sensitivity need to be attained. Secondly we have reviewed a general approach to gray-scale modulation coding and pointed out the general construction rule for common constant-weight codes. Finally we investigated the amount of data security provided by random phase-code encryption, which was formerly pronounced to be very efficient. It turned out to be less efficient than encryption based on arithmetic data page operations when abusing the capability of content-addressing in a phase-encoded volume holographic storage system.

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